10306 Session 2022
Study Committee B2
PS3 Environmental and Safety Aspects from OHL

Altitude Correction Method of Electromagnetic Environment for HVDC Transmission Line and Its Engineering Application

Luxing ZHAO[1] zhaolx@epri.sgcc.com.cn, Lei GAO[2] gaolei@xz.sgcc.com.cn, Jiayu LU[1] lujy@epri.sgcc.com.cn, Chao LIU[2] lc@xz.sgcc.com.cn, Li XIE[1] xieli@epri.sgcc.com.cn, Yong JU[1] juyong@epri.sgcc.com.cn, Feng BAI[1] baifeng@epri.sgcc.com.cn
1. China Electric Power Research Institute
2. Electric Power Research Institute of State Grid Tibet Electric Power Co., Ltd.
China

SUMMARY

With the implementation of China's west-east power transmission program, the HVDC transmission lines passing through high altitude areas have increased year by year, with some lines reaching altitudes of 3,000 meters to 5,000 meters. The accuracy of the prediction of the electromagnetic environment of high-altitude DC lines is directly related to project investment and environment protection, but there is no systematic research on it at home and abroad. Prediction and control of the electromagnetic environment of HVDC transmission lines at high altitudes has become a key technical issue that needs to be solved in the development of E/UHVDC transmission technology in China. Four DC scale-model test lines under the same parameters are built up at 50m, 1,700 m, 3,400 m and 4,300 m elevations. Simultaneously, the same type of overhead conductors had been set up on two DC full-scale test lines, whose altitudes are 50 m and 4,300 m. Using the test facilities above, total electric field (TEF) and audible noise (AN) of the HVDC transmission line are measured for a long term in different altitudes and test voltages.

Based on the analysis of the test results of the ground-level TEF at different altitudes, it is revealed that the maximum of the ground-level electric field increases linearly with the increase of altitude. With the increase of electric field strength on the conductor surface, the increased rate of ground-level TEF decreases gradually with the increase of altitude. The altitude correction formula of ground-level TEF for HVDC transmission lines is proposed to solve the difficulty of predicting DC ground-level TEF in high altitude regions based on that at low altitudes (0m above sea level).

Based on the long-term AN test of the reduced-scale test lines and full-scale test lines at altitude 50 m-4,300 m, it is revealed that the increase of AN of the HVDC transmission lines varies nonlinearly with the increase of altitude, i.e., in the range of 50 m-4,300 m, with the increase of altitude, AN increases slowly, rapidly and slowly. The altitude correction formula of AN for HVDC transmission lines is proposed, which solved the technical bottleneck in the prediction of AN and the selection of conductors for HVDC transmission lines at high altitudes. The AN of HVDC transmission lines at different altitudes predicted by the formula proposed in this paper is smaller than that predicted by the formula recommended by EPRI. The application of this method in the design of HVDC transmission lines at high altitudes could save heavy investment while meeting the requirements of environmental protection.

Based on the prediction method of high altitude HVDC electromagnetic environment proposed in this paper, the minimum conductor type and optimal line structure parameters of ±500kV HVDC transmission lines are recommended to meet the requirements of the electromagnetic environment in the altitude range of 0-4,300m. The research results can ensure that the electromagnetic environment of the HVDC transmission line meets the environmental protection limit and realize the saving of project investment.

KEYWORDS

Total electric field; AN; electromagnetic environment; HVDC; transmission line; altitude correction

0. Introduction

To improve the cost-effectiveness of long-distance, high-capacity transmission, China has adopted HVDC transmission technology. At the same time, as the public awareness of environmental protection has enhanced, electromagnetic environment has become a major technical problem that must be considered in the design and construction of DC transmission projects[1]. China has vast territory, where HVDC transmission lines are widely distributed. From west to east, the altitude span is large. Therefore, the problem of high altitude is inevitable for the development of DC transmission technology[2].Among DC projects that have been completed and put into operation, the maximum altitude of Sichuan Jinping - Jiangsu Suzhou ±800kV UHVDC transmission line, Gansu Jiuquan - Hunan Xiangtan ±800kV UHVDC transmission line and Qinghai Golmud - Tibet Lhasa ±400kV HVDC transmission lines are 3,400 m, 3,100 m and 5,300 m respectively.

The electromagnetic environment of DC transmission lines mainly includes DC total electric field(TEF) and AN(AN), which are directly related to corona discharge. With the increase of altitude, air density decreases, free path of electrons increases, accumulated kinetic energy of electrons in a free path increases, and the probability of ionization after collision of electrons with air molecules increases, resulting in easier corona discharge on the surface of the conductor. Under the same line voltage and line structure, electromagnetic environment problems caused by corona discharge in high-altitude areas are more serious than those in low-altitude areas[3]. As the same environmental protection standards are implemented in high-altitude areas and low-altitude areas, it is necessary to take measures such as increasing conductor sections and raising the height of the line to the ground when constructing HVDC transmission lines in high-altitude areas, to ensure the electromagnetic environment of the HVDC transmission line meets the requirements of environmental protection limits. This will undoubtedly increase project cost. Therefore, the accuracy of the electromagnetic environment prediction method for high-altitude HVDC transmission lines has become a key technical issue that must be focused on.

At present, a large number of experimental studies have been carried out on the AC transmission lines electromagnetic environment at high altitudes, and the altitude correction method of electromagnetic environment proposed has been tested in practice and widely used in the design of high-altitude AC transmission lines[4,5]. However, in the field of electromagnetic environments of DC transmission lines, there are almost no high-altitude DC transmission projects at high voltage level abroad, so the research on the electromagnetic environments of high-altitude DC transmission lines is almost blank. The Electric Power Research Institute (EPRI) recommended an altitude correction method of AN of DC transmission lines in the *HVDC Transmission Line Reference Book* published in 1993[6]. However, the AN correction method is exactly the same as that of AC transmission lines, which is based on the conclusion of AC transmission lines, instead of originating from experimental study of high altitude HVDC transmission lines. From the perspective of corona discharge mechanisms and influencing factors, there are so many differences between AC transmission lines and DC transmission lines that it is still controversial whether the altitude correction method recommended by EPRI can be applied to HVDC transmission lines.

To deeply study the characteristics of electromagnetic environments of HVDC transmission lines in high-altitude areas and its variation with altitude, State Grid Corporation of China(SGCC) built DC full-scale test lines with the same structure in Yangbajing (Tibet) at an altitude of 4,300 m and Changping (Beijing) at an altitude of 50 m, and four DC reduced-scale test lines with consistent parameters at altitudes of 50 m, 1,700 m, 3,400 m and 4,300 m. In the past six years, detailed experimental studies on the electromagnetic environment of HVDC transmission lines at different altitudes and voltages have been carried out by using the above-mentioned test means . The electromagnetic environment level and distribution law of HVDC transmission lines at different altitudes is obtained. Through statistical analysis of test data, an altitude correction method of electromagnetic environment of HVDC transmission lines is put forward, providing a technical basis for the economic and reasonable design of HVDC transmission lines in high-altitude areas. The paper summarizes the above study achievements.

1. Test lines at different altitudes

This paper studies the influence of altitude on electromagntic environment of HVDC transmission line by combining full-scale test and reduced-scale test. The function of reduced-scale test is to obtain the rule of the electromagnetic environment of HVDC transmission lines changing with altitude through experiments and propose an altitude correction model. The function of full-scale test is to obtain the actual altitude increase of electromagnetic environment.

The DC reduced-scale test lines adopt double pole and single circuit erection, with a length of 100 m. The conductor type is 4×LGJ-95/15; pole spacing is 6 m; and ground height of the lowest point of the pole conductor is 7m. The altitude of the construction site is 50 m (Nanshao Town, Changping, Beijing), 1,700 m (Xiachayu Town, Linzhi, Tibet), 3,400 m (Bahe Town, Linzhi, Tibet) and 4,300 m (Yangbajing Town, Lhasa, Tibet). The actual scenes of the test lines are shown in Figure 1.

(a) Altitude of 50 m (b) Altitude of 1,700 m

(c) Altitude of 3,400 m (d) Altitude of 4,300 m

Figure 1 DC reduced-scale test line at different altitudes

The DC full-scale test lines are located in Tibet and Beijing respectively. The altitude of full-scale test lines in Tibet and Beijing is 4,300 m and 50 m respectively. The length of the full-scale test lines are 300 m, and the minimum ground height of the lines from the middle span are both 15 m. The actual scenes of full-scale test lines at two altitudes are shown in Figure 2.

(a) Test line in Tibet (high altitude of 4,300 m) (b) Test line in Beijing (altitude of 50 m)

Figure 2 DC full-scale test lines at different altitudes

2 Altitude correction method of ground-level TEF of HVDC transmission line

2.1 Ground-level TEF test of DC reduced-scale test lines at different altitudes

By using four DC reduced-scale test lines within altitudes of 50 m – 4,300 m, a long-term test of DC ground-level TEF is carried out, and the total amount of effective sample data is more than 130,000 groups. When performing DC reduced-scale tests, the voltage range applied to the test line ranges from ±150kV to ±300kV.

For ground-level TEF of HVDC transmission lines, the absolute value of the maximum electric field strength under the line is generally used as the main evaluation index in environmental evaluation. Therefore, when studying the impact of altitude on DC ground-level TEF, the absolute maximum of positive and negative ground-level TEF is selected as the main research object. Due to the large dispersion of test data of the DC ground-level TEF, the method of cumulative percentage probability is generally used for data processing. Figure 3 shows the variation curve of ground-level TEF with altitude under different conductor surface electric field strengths. As shown in the Figure, ground-level TEF strengthgradually increases with increasing altitude. The difference is that when the conductor surface electric field strength is small, the increase range is fast and the slope of the corresponding curve is larger. When the conductor surface electric field strength is large, the increased range of the ground-level TEF gradually decreases, and the slope of the corresponding curve also gradually decreases.

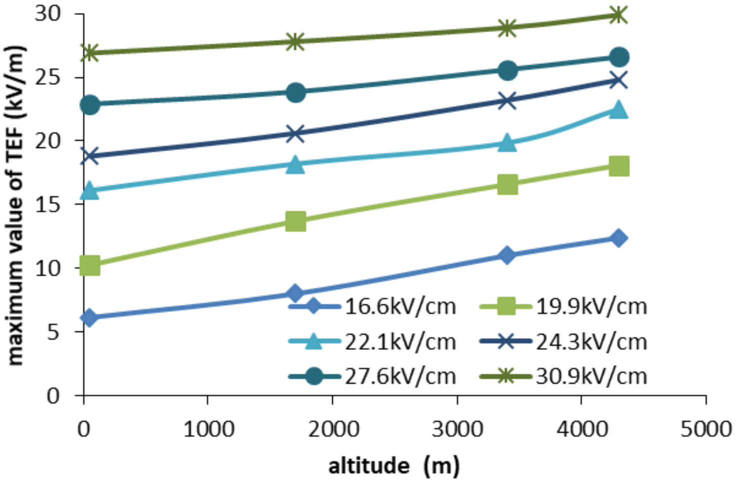

Fig. 3 Variation curve of ground-level TEF with altitude under different conductor surface electric field strength

By observing the shapes of the TEF variation curves corresponding to different conductor surface electric field strengths with altitude in Figure 3, the maximum vlalues of the ground-level TEF increase linearly with the altitude. Therefore, the univariate linear regression model is used to reflect the relationship between the ground-level TEF and altitude. The fitting formula is:

$$E_H = E_L\left(1+kH\right) \qquad (1)$$

where, E_L - test value of TEF at an altitude of 0 m, kV/m;

H - altitude, km;

E_H - predicted value of ground-level TEF at altitude H, kV/m;

k - altitude correction coefficient of ground-level TEF, indicating an increase rate of ground-level TEF for every 1,000 m increase in altitude.

2.2 Altitude correction formula of ground-level TEF based on full-scale test lines.

By using the Beijing-Tibet DC full-sacle test line, two types of conductors (4×LGJ-500/45 and 6×LGJ-300/40) are set up, and a long-term test of DC ground-level TEF is carried out. The polarity distance of the test lines are both 22 m; the height of the central conductor of the span to the ground 15 m; and test voltage ranges ±500kV to ±700kV.

In the same way as the analysis of reduced-scaled test lines, ground-level TEF results of the full-scale test lines in the medium humidity range (40% - 60%) are selected for statistical analysis and comparison. Table 1 shows the statistical mean of the maximum of ground-level TEF when different conductors and voltages.

Table 1 Statistical mean values of maximum ground-level TEF of DC full-scale test lines at different altitudes

Conductor type	Voltage (kV)	Conductor surface electric field strength (kV/cm)	Ground-level TEF (kV/m)	
			Altitude 50 m	Altitude 4,300 m
6×LGJ-300/40	±500	19.65	17.0	27.2
4×LGJ-500/45	±500	20.96	18.0	27.6
	±600	25.69	27.6	32.8
	±700	29.97	34.0	38.7

According to Table 1, the higher the altitude, the greater the ground-level TEF. From an altitude of 50 m to 4,300 m, under the voltage of ±500kV, the increase of ground-level TEF of 6×LGJ-300/40 conductor is 10.2kV/m, the increase of ground-level TEF of 4×LGJ- 500/45 conductor is 9.6kV/m. There is little difference between the two conductors. The main reason is that the equivalent electrical radius of the two conductors are not much different, so their corona characteristics are also very close. For the same kind of conductor, with an increase of conductor surface field strength, elevation increases of ground-level TEF decreases gradually.

According to the research conclusion of the ground-level TEF of the DC reduced-scale test lines, the univariate linear function could be used to characterize the influencing law of altitude on the ground-level TEF of the full-scale test lines. The altitude correction formulas of the ground-level TEF of HVDC transmission lines under different conductor surface field strength are obtained, as shown below.

$$6 \times \text{LGJ-300/40 conductors, } E_s\text{=19.65kV/cm:} \quad E_H = E_L\left(1+0.14H\right) \tag{2}$$

$$4 \times \text{LGJ-500/45 conductors, } E_s\text{=20.96kV/cm:} \quad E_H = E_L\left(1+0.124H\right) \tag{3}$$

$$4 \times \text{LGJ-500/45 conductors, } E_s\text{=25.69kV/cm:} \quad E_H = E_L\left(1+0.044H\right) \tag{4}$$

$$4 \times \text{LGJ-500/45 conductors, } E_s\text{=29.97kV/cm:} \quad E_H = E_L\left(1+0.032H\right) \tag{5}$$

The coefficient k in the altitude correction formula gradually decreases with an increase of conductor surface electric field strength in Equations (2) to (5). Under ±500kV voltage, conductor surface field strength ranges from 19.65kV/cm to 20.97kV/cm. Within a range of altitude below 4,300m, the ground-level TEF of DC transmission lines increases by about 12 - 14% for every 1,000m increase in altitude. According to the above research results, the ground-level TEF of HVDC transmission lines at different altitudes could be obtained on the basis of low altitude ground-level TEF and different altitude corrections.

3 AN altitude correction method of HVDC transmission lines

3.1 AN altitude correction based on DC reduced-scale test

Long-term AN tests of the reduced-scale test lines are carried out by using four DC reduced-scale test lines located in Changping (Beijing), Xiachayu (Tibet), Bahe (Tibet) and Yangbajing (Tibet). The total volume of test data obtained is more than 100,000 groups, and the test time covers different seasons and different climatic conditions.

Considering the number of samples in the range of different meteorological parameters, the AN test data in the range of 40 - 60% is selected for statistical analysis in the paper. According to the AN transverse distribution law, within the common conductor surface electric field strength range of DC transmission lines, the level of AN under the positive conductor is largest, and data outside the positive conductor is generally emphasized in the engineering design. Therefore, for the AN test data at different altitudes and voltages, the statistical average (50% value) of test results under the positive conductor is taken for comparison, as shown in Table 2.

Table 2 The statistical average results of AN of DC reduced-scaled test lines at different altitudes

Voltage (kV)/conductor surface electric field strength (kV/cm)	Statistical average of AN [dB(A)]				Altitude correction of AN [dB(A)]		
	50m	1700m	3400m	4300m	1700m-50m	3400m-50m	4300m-50m
200/22.04	31.15	31.55	35.42	36.50	0.40	4.27	5.35
220/24.24	34.76	35.61	41.04	42.61	0.85	6.28	7.85
250/27.55	41.38	42.87	48.62	51.97	1.49	7.24	10.59
280/30.86	43.42	46.22	51.29	52.94	2.80	7.87	9.52

From altitude 50 m to 4,300 m, with an increase of altitude, AN under the DC reduced-scale test lines also increases, but showing a non-linear variation law, that is, showing a trend of slow increase - rapid increase - slow increase, which is completely different from the noise characteristics of AC transmission lines. The reason may be that the polarity of DC transmission line is single. With a continuous increase of altitude, after the corona discharge on the conductor surface is enhanced to a certain extent, an ionosphere with a certain thickness is formed near the conductor surface, that is, the so-called “diameter expansion effect”, which plays a role in restraining the corona discharge, thus causing the slow increase of AN.

According to the variation characteristics of AN in different altitude ranges, the AN altitude correction curve of HVDC transmission lines is fitted by a non-linear formula. When fitting, the altitude 50 m is approximately 0 m.The form of fitting function is determined as follows:

$$\Delta_{AN} = k_{AN} \Big/ \left[1 + \mathrm{e}^{a(x+b)}\right] \tag{6}$$

where, Δ_{AN} represents the AN altitude correction, dB (A); x represents the altitude, m; k_{AN}, a and b represent undetermined coefficients. The least square method is used to solve the coefficients k_{AN}, a and b, the values of the fitting formula coefficients k_{AN}, a and b of the AN altitude correction of the DC reduced-scale test line under different conductor surface field strengths could be obtained, as shown in Table 3. The AN altitude correction curve calculated by the above altitude correction formula has a good fit with the calculated value of the formula, the correlation coefficients are above 0.97, and the RMSE is not greater than 0.9 dB, indicating that it is reasonable to use Equation (6) as the AN altitude correction reference function of DC transmission line.

Table 3 Coefficients of altitude correction fitting formula of AN

Voltage (kV)	Conductor surface electric field strength (kV/cm)	k_{AN}	a	b	Correlation coefficient R	RMSE (dB)
±200	22.08	5.85	-0.0018	-2900	0.9986	0.122
±220	24.29	8.61			0.9995	0.104
±250	27.60	11.00			0.9957	0.398
±280	30.86	10.71			0.9732	0.879

3.2 AN altitude correction method based on DC full-scale test lines

At an altitude 50 m and 4,300 m, 4×LGJ-500/45 are set up in Beijing and Tibet respectively by using two full-scale test lines. A long-term tests of AN under different voltages and meteorological conditions are carried out. During the tests, the voltage ranges arefrom ±500kV to ±700kV. As for the AN test results of DC full-scale test lines at the altitudes of 50 m and 4,300 m, the handling method is similar to that of the reduced-scale test lines, and the data of relatively consistent meteorological conditions is also selected for comparison. The humidity range and wind speed range corresponding to the data selected in the paper are 40 - 60% and less than 2 m/s respectively. The comparisons of AN test results of full-scale test lines at altitudes of 4,300 m and 50 m under the positive conductors after statistics are shown in Table 4.

Table 4 Comparisons of AN of full-scale test lines at different altitudes with 4×LGJ-500/40 conductors

Voltage (kV)/ Conductor surface electric field strength (kV/cm)	Statistical average of AN [dB (A)]		
	Altitude 50 m	Altitude 4,300 m	AN correction (4,300 m - 50 m)
500kV/21.41	34.49	39.41	4.92
600kV/25.69	39.94	47.39	7.45
650kV/27.83	41.41	49.43	8.02
700kV/29.97	43.74	51.02	7.28

According to comparisons of AN test results of reduced-scale test lines and full-scale test lines at altitudes of 50 m and 4,300 m, when the conductor surface electric field strength of the full-scale test line is 21.4kV/cm, the AN difference at altitudes of 4,300 m and 50 m is 4.92 dB (A). As for reduced-scale test lines, when the conductor surface electric field strength is 22kV/m, the AN difference of the above two altitudes is 5.35 dB (A), with very small differences on that of full-scale test lines. Therefore, although the conductor types are different in full-scale test lines and reduced-scale test lines, they are both bundled conductors and the equivalent electrical radiuses are not much different, so the change rule of AN with altitude should be consistent. It means that the AN altitude correction formula for full-scale test lines could also be represented with a non-linear formula, that is $\Delta_{AN} = k_{AN} \Big/ \left[1 + \mathrm{e}^{a(x+b)}\right]$. In the formula, the values of correction factors *a* and *b* are consistent with those in reduced-scale test lines, which are -0.0018 and -2900 respectively, and only the correction coefficient k_{AN} is different. The calculation formula for AN altitude correction of full-scale test lines is shown as follows:

$$\Delta_{AN} = k_{AN} \Big/ \left[1 + \mathrm{e}^{-0.0018(x-2900)}\right] \tag{7}$$

It is assumed that the altitude of 50 m is approximate to the altitude of 0 m, and based on the least square method, the coefficient k_{AN} in the AN altitude correction formula of full-scale test lines under different conductor surface electric field strengths could be obtained, as shown in Table 5.

Table 5 k_{AN} values in altitude correction formulas of AN for the full-scale test line

Voltage (kV)	Conductor surface electric field strength (kV/cm)	k_{AN}	Correlation coefficient R
±500	21.41	5.31	0.9999
±600	25.69	8.05	0.9999
±650	27.83	8.67	0.9999
±700	29.97	7.87	0.9999

3.3 Comparisons of the AN altitude correction method in this paper and the recommended method by EPRI

The difference between the AN altitude correction method of DC transmission lines proposed in this paper and the EPRI prediction method is compared as follows. During comparison, 4 × LGJ-500/40 conductors are used, line polarity distance is 22 m, and minimum height of the conductor to the ground is 15 m.

According to the research report of EPRI[6], the recommended AN altitude correction method of DC transmission lines is “The AN will increase by 1 dB (A) in case of an altitude increase relative to sea level for every 300 m.” Therefore, the altitude correction formula can be expressed as

$$\Delta_{AN} = \frac{1}{300} x \tag{8}$$

where, x - altitude, m

Δ_{AN} - AN increase, dB (A).

The AN altitude increase of DC transmission lines obtained by the method proposed in this paper and the EPRI prediction method within the range of 50 m - 4,300 m are shown in Fig 4.

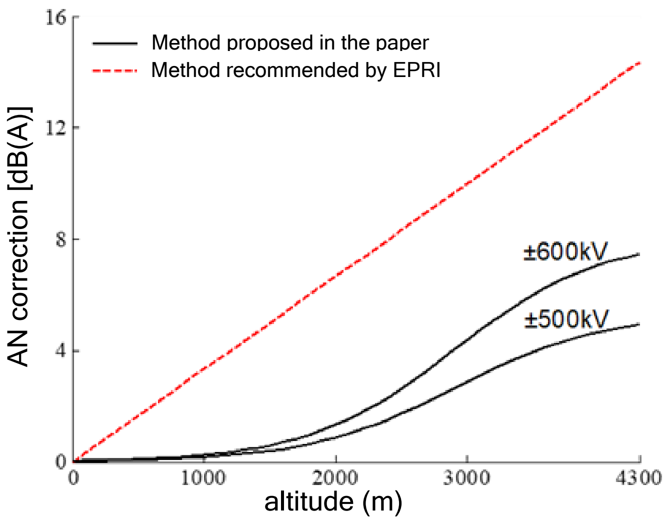

Fig. 4 Comparison of AN altitude correction formula of HVDC transmission lines proposed in this paper and the method recommended by EPRI

According to the figure, the AN of HVDC transmission lines at different altitudes, predicted by the altitude correction formula proposed in this paper, is far less than results predicted by the EPRI formula. Taking ±500kV as an example, from altitudes 0 m to 4,300 m, the AN increase predicted by the AN altitude correction formula of DC transmission lines obtained in this paper is 4.92 dB(A), which is 35% of the value predicted by the EPRI formula. When the altitude is from 0 m to 3,400 m and from 0 m to 1,700 m, the noise increase is respectively 3.82 dB(A) and 0.56 dB(A) predicted by the formula in this paper, and 11.3 dB(A) and 5.67 dB(A) predicted by the EPRI formula. The former ones are only 34% and 10% of the later ones.

4 Engineering application

When DC transmission lines pass through high-altitude areas, the selection of conductor types are mainly determined by AN. AN levels of ±500kV DC transmission lines passing through high-altitude areas with different conductors calculated by the altitude correction method of EPRI and the one proposed in this paper are shown in Table 6. In the calculation, the line polarity distance set is 18 m, minimum height of the conductor to the ground is 15 m, and sag is 20 m. The AN prediction method at low altitudes adopts ERPI's formula.

Table 6 AN of 20 m from the projection of positive conductors of HVDC transmission lines at different altitudes

Conductor type		4×400 mm^2	4×500 mm^2	4×630 mm^2	4×720 mm^2	6×300 mm^2	6×300 mm^2
Conductor diameter (mm)		27.6	30	33.8	36.23	23.9	27.6
Bundle spacing (m)		0.45	0.45	0.45	0.45	0.4	0.4
Conductor surface electric field strength (kV/cm)		23.26	21.71	19.7	18.63	19.96	17.74
AN calculation results at an altitude of 0 m [dB (A)]		38.11	35.30	31.70	29.11	31.49	26.70
AN calculation results at an altitude of 3,000 m [dB (A)]	Method recommended by EPRI	48.11	45.30	41.70	39.11	41.49	36.70
	Method proposed in this paper	41.79	38.31	33.83	30.80	33.73	28.07
AN calculation results at an altitude of 4,000 m [dB (A)]	Method recommended by EPRI	51.44	48.63	45.03	42.44	44.82	40.03
	Method proposed in this paper	44.04	40.16	35.13	31.84	35.09	28.91

If the AN generated by corona at 20 m from the projection of positive conductors is required to not exceed 45 dB (A), according to the calculation results for ±500kV DC transmission lines, if the EPRI altitude correction method is used, when the altitude is 4,000 m, it is necessary to use 4 × 630 mm^2 or 6 × 300 mm^2 conductors. However, according to the research results in this paper, in areas with an altitude of 4,000 m, 4 × 400 mm^2 conductors can reduce AN at 20 m from the projection of positive conductors to below 45 dB (A). The application of the AN altitude correction method proposed in this paper in DC transmission lines at high altitudes can avoid wrong conductor type selection due to inaccurate prediction formula, and greatly save line investment while meeting environmental protection requirements.

5 CONCLUSION

In view of the key problem of electromagnetic environment prediction and control at high altitudes faced in the development of HVDC transmission technology, a long-term test of DC ground-level TEF and AN is carried out by taking advantages of two full-scale test lines in Beijing (altitude of 50 m) and Tibet (altitude of 4,300 m) respectively, and four DC reduced-scale test lines are established at different altitudes from 50 m to 4,300 m to study the altitude correction method for electromagnetic environments of HVDC transmission lines.

(1) According to the experimental study on ground-level TEF of DC transmission lines at different altitudes from 50 m to 4,300 m, the rule that the maximum of ground-level TEF increases linearly with the increase of altitude basically is revealed, and with the increase of conductor surface field strength, the increasing rate of ground-level TEF with the increase of altitude gradually decreases. The altitude correction formula for ground-level TEF of HVDC transmission lines is proposed based on the ground-level TEF tests of DC test lines at different altitudes.

(2) According to the study on AN tests of DC lines at different altitudes, an important rule that the AN increase of DC transmission lines has non-linear changes with the increase of altitude is revealed. In the altitude range of 50 m-4,300 m, with the increase of altitude, AN shows a characteristic of slow increase - rapid increase - slow increase. The AN altitude correction formula of HVDC transmission lines at altitudes from 0 m to 4,300 m is proposed, solving technical bottlenecks encountered in AN prediction, conductor type selection and other aspects of HVDC transmission lines at high altitudes.

(3) Because AN of HVDC transmission lines at different altitudes predicted by the altitude correction formula proposed in this paper is far less than results predicted by the recommended formula of EPRI, this formula is applied in the design of HVDC transmission lines at high altitudes, which can greatly save line investment while meeting environmental protection requirements.

ACKNOWLEDGMENT

The research was supported by the Science and Technology Project of State Grid Corporation of China "Research on Key Technologies of Electromagnetic Environment, External Insulation and Lightning Protection of UHV Transmission Lines at High Altitude Areas".

BIBLIOGRAPHY

[1] Liu Z, Yu J, Guo X, et al. *Survey of Technologies of Line Commutated Converter Based High Voltage Direct Current Transmission in China*. CSEE Journal of Power and Energy Systems, 2015, 1(2): 1-8.

[2] Sun X, Liu Z, Gao L, et al. *Practice and Innovation in the ±800kV UHVDC Demonstration Project*. Proceedings of CSEE, 2009,29(22):35-45.

[3] Maruvada P S. *Corona Performance of High-Voltage Transmission Lines* London: Research Studies Press, 2000

[4] V. L. Chartier, L. Y. Lee, L. D. Dickson, and K. E. Martin. *Effect of High Altitude on High Voltage AC Transmission Line Corona Phenomena*. IEEE Trans. Power Del., vol. PWRD-2, no. 1, pp. 225–237, Jan. 1987.

[5] Tang J, Hui J Liu Y. *Test Results and Analysis of Altitude-change Effect on Audible Noise of AC Corona Occurring on Conductors with Corona-Test Cage*. Proc. CSEE, vol. 30, no. 4, pp.105-111, Feb. 2010.

[6] EPRI Report TR-102764. HVDC Transmission Line Reference Book Palo Alto: EPRI, 1993